Weed Science, 49:571–577. 2001

Imazaquin mobility and persistence in a Sharkey clay soil as influenced by tillage systems

Simone Seifert
Department of Plant and Soil Sciences, Mississippi State University, Mississippi State, MS 39762

David R. Shaw
Corresponding author. Department of Plant and Soil Sciences, Mississippi State University, Mississippi State, MS 39762; dshaw@rstc.msstate.edu

William L. Kingery
Department of Plant and Soil Sciences, Mississippi State University, Mississippi State, MS 39762

Charles E. Snipes
Delta Research and Extension Center, Mississippi State University, Stoneville, MS 38776

Richard A. Wesley
USDA/ARS, Application and Production Technology Research, Stoneville, MS 38776

Field studies were conducted at Delta Research and Extension Center, Stoneville, MS, in 1996, 1997, and 1998 to assess the effect of tillage systems (conventional tillage and subsoiling) on the environmental fate of imazaquin in a Sharkey clay soil. Imazaquin was applied preemergence at 140 g ai ha^{-1}. Subsoiling in the fall did not affect imazaquin dissipation, total volume of runoff, imazaquin concentration in runoff, or imazaquin concentration in soil, as determined by chemical extraction. A corn root bioassay revealed no differences due to tillage systems in plant-available imazaquin in soil. Imazaquin concentration measured by chemical extraction or bioassay diminished over time, with a half-life ranging from 8 to 25 d. A field bioassay utilizing cotton and corn was conducted in 1997 and 1998 using plots that had received imazaquin the previous year. In 1997, 2 wk after planting, cotton and corn injury ranged from 3 to 15%, whereas no injury was observed in 1998. Injury symptoms declined over time, with no injury 5 wk after planting in either year. Although early-season cotton stunting and slight discoloration of corn was apparent in 1997, imazaquin residues did not affect subsequent vegetative and reproductive growing patterns of cotton or corn. In 1998, corn and cotton height were significantly greater in subsoiled plots compared to conventional tillage.

Nomenclature: Corn, *Zea mays* L. 'HyPerformer HS 9773', 'Pioneer 3167'; cotton, *Gossypium hirsutum* L. 'DPL 50'; soybean, *Glycine max* (L.) Merr. 'DPL 3589'.

Key words: Bioassay, carryover, dissipation, field dissipation, plant availability, runoff, subsoiling.

Imazaquin, a member of the imidazolinone herbicide family, is widely used for broadleaf and grassy weed control in soybean and warm-season turfgrasses. When applied preplant incorporated (PPI), preemergence (PRE), or postemergence (POST), imazaquin can provide season-long control of various troublesome weeds, including common cocklebur (*Xanthium strumarium* L.), giant foxtail (*Setaria faberi* Herrm.), sicklepod [*Senna obtusifolia* (L.) Irwin and Barnaby], and velvetleaf (*Abutilon theophrasti* Medic.). Similar to other acetolactate synthase (ALS)-inhibiting herbicides, imazaquin is absorbed by roots and shoots and translocated to meristematic areas (Ahrens 1994).

Imazaquin is an ionizable organic molecule, containing both an ionizable carboxyl group with a pK_a of 3.8 and a basic quinoline ring with a dissociation constant of 2.0 (Goetz et al. 1986; Loux et al. 1989; Regitano et al. 1997). At near-neutral pH levels, normal for most agricultural soils, imazaquin is principally present as the deprotonated anion. Because most soils have a net negative charge, strong repulsive coulombic forces result in low adsorption of the imazaquin anion (Regitano et al. 1997). However, imazaquin adsorption increases as pH decreases, which may result in extended persistence under certain soil and environmental conditions (Basham et al. 1987; Goetz et al. 1986; Loux and Reese 1992; Loux et al. 1989) and injury to rotational crops such as corn, barley (*Hordeum vulgare* L.), cotton, and certain vegetable crops (Barnes and Lavy 1991; Curran et al. 1992; Johnson and Talbert 1996; Johnson et al. 1995; Mills and Witt 1991).

A large percentage of heavy clay or clayey mixed soils in the Mississippi Delta exhibit high shrinking and swelling properties. These soils have a high content of 2:1 layer-expandable smectitic clay minerals and are characterized by a high cation exchange capacity (cec) and slow permeability and internal drainage. Tillage systems affect the surface soil zone by affecting the amount of organic residues present and the degree of soil disturbance and by causing temporal changes in soil physical and chemical properties, including pH, soil moisture, temperature, biological activity, and soil structure (Griffith et al. 1992; Locke and Bryson 1997). Subsoiling or deep tillage applied in the fall increases yield of nonirrigated soybean grown on Tunica and Sharkey clay soils (Wesley and Smith 1991; Wesley et al. 1994). This higher yield potential, especially in dry seasons, has been attributed to increased water infiltration rates, water storage capacity, and enhanced depth of profile wetting (Wesley et al. 1994). Using a subsoiler equipped with parabolic shanks creates only a small slot in the soil surface. Thus, the degree of soil disturbance is considerably lower compared to conventional tillage. Although the depth of tillage is increased, subsoiling leaves more plant residues on the soil surface.

Therefore, tillage systems can directly or indirectly affect the performance and persistence of soil-applied herbicides. Increased organic matter as a result of elevated levels of plant residues at the soil surface and minimal soil disturbance can provide additional adsorption sites for organic molecules. Adsorption removes herbicide molecules from the soil solution, thereby protecting them from plant uptake, leaching, microbial and chemical breakdown, volatility, and photodecomposition, and it prolongs the persistence of some herbicides (Locke and Bryson 1997; Mills and Witt 1991).

Although subsoiling has been shown to be beneficial in several soil types from a yield standpoint, limited research has been conducted to predict the effect of subsoiling on the environmental fate of soil-applied herbicides in heavy clay soils. Therefore, the objective of this study was to determine the effect of tillage systems (conventional tillage and subsoiling) on imazaquin bioavailability, persistence, and carryover potential in a Sharkey clay soil in the Mississippi Delta.

Materials and Methods

Site and Soil

Field studies to evaluate the effect of tillage systems on imazaquin dissipation in a smectitic clay soil were conducted in 1996, 1997, and 1998 at the Delta Research and Extension Center, Stoneville, MS. The soil type evaluated was a Sharkey clay (very fine, smectitic, thermic Chromic Epiaquert) and was characterized by a high percentage of clay (66%) with 2.9% organic matter, poor internal drainage, and pH 6.4. Two tillage systems, conventional tillage and parabolic subsoiling, were evaluated. Tillage treatments had been initiated 3 yr prior to the study and remained in the same plots for the 3-yr test period. Subsoiling, done each fall during the study, was performed with a subsoiler equipped with two parabolic shanks spaced 1 m apart extending approximately 40 to 45 cm into the soil. Although subsoiled plots were tilled with a spike-tooth harrow to smooth out rough areas, the soil was less disturbed compared to conventionally tilled plots. Conventional tillage, also done each fall, was performed with three passes with a disk-harrow operating 15 cm deep, followed by a field cultivator. Paraquat at 1.1 kg ai ha^{-1} was applied to eliminate all winter vegetation prior to planting.

Soybean DPL 3589 was planted on May 15, 1996, June 4, 1997, and June 3, 1998, to a depth of 3 cm at a rate of 33 seeds m^{-1} of row. Immediately after planting, imazaquin was applied at a rate of 140 g ai ha^{-1} using a CO_2-pressurized backpack sprayer calibrated to deliver 187 L ha^{-1} at a pressure of 195 kPa. Untreated plots receiving no imazaquin were included for comparison. No imazaquin had been applied to the site prior to initiation of the study. Plots were 9 m long and contained six rows spaced 1 m apart. All plots were maintained weed-free season long by hand hoeing and mechanical cultivation.

Runoff

In 1997 and 1998, the two center rows of imazaquin-treated plots were bordered with metal flashing to exclude outside runoff, creating a runoff collection area 9 by 1 m. The runoff effluent was allowed to accumulate in catch basins located at the end of each imazaquin-treated plot. Within 12 h of each natural rainfall, runoff effluent was recovered. After total runoff, water was quantified, the effluent was agitated, and a sample of approximately 600 ml was obtained and stored at 4 C until analysis.

Water samples were vacuum filtered through a buchner funnel fitted with a 9-cm-diam filter paper[1] following pH adjustment to pH 2.0 with 6 *N* HCl. Imazaquin residues in water samples were extracted using a 16 h liquid–liquid extraction followed by high-performance liquid chromatography (HPLC) analysis. A 500-ml aliquot of each water sample was transferred into a liquid–liquid extractor containing 250 ml methylene chloride. A 500-ml flat-bottomed flask with 300 ml methylene chloride was attached to a water-cooled condenser and extractor body, then placed on a hot plate. Extraction continued for 16 h at 215 C. The sample obtained in the 500-ml flask was concentrated to dryness by rotary evaporation. Concentrated extracts were passed through a 20-μl syringe filter[2] and brought to 5 ml volume using pH 6.5 potassium phosphate buffer. A HPLC[3] equipped with a diode-array detector set at a wavelength of 240 nm was adjusted to inject a volume of 250 μl. HPLC separation was performed using a C-18 reversed-phase column[4] with the initial mobile phase of water (adjusted to pH 3.0 with acetic acid) : acetonitrile (50:50, v/v) at a flow rate of 1 ml min^{-1}.

Field Mobility and Persistence

Soil samples were collected 0, 1, 2, 3, 4, and 8 wk after treatment (WAT) in 1996 and 1998 and at 0, 2, 3, 4, 6, and 8 WAT in 1997. At each sampling date, 20, 2-cm-diam by 15-cm deep cores were randomly taken to obtain soil samples from 0 to 8 cm deep (approximately 300 g each). Samples were frozen at −15 C immediately after collection until analysis. Prior to analysis, samples were allowed to air dry at room temperature and passed through a 3-mm screen.

Imazaquin was extracted from soil using a method developed by American Cyanamid Company.[5] The herbicide residue was extracted from 50 g of air-dried soil (oven-dry wt) using 150 ml of 0.5 N NaOH solution (30% methanol/70% water) for 1 h on a reciprocal shaker. Fifteen grams of celite[6] was added and samples were vacuum filtered through a buchner funnel fitted with a 9-cm-diam single-layer Whatman filter paper.[7] After washing the filter cake with approximately 30 ml of extraction solution, the extract was brought to a 200-ml volume. The pH of an aliquot of 100 ml was adjusted to 2.0 with 6 *N* HCl to precipitate the humic acid fraction. Twenty grams of sodium chloride was added prior to sample cleanup. Imazaquin residues were passed through analytical bond elut octadecyl (C-18) cartridges[8] and analytical bond elut benzene sulfonic acid (SCX) cartridges.[9] The octadecyl cartridge was first prepared by passing 3 ml of methanol followed by 3 ml of distilled water, and the benzene sulfonic acid cartridge was prepared with 3 ml of hexane, 3 ml of methanol, and 3 ml of distilled water in succession. The herbicide samples were first passed through the octadecyl cartridges and then eluted with 50% aqueous methanol solution into a benzene sulfonic acid cartridge at a rate of 2 drops min^{-1}. Following filtration, benzene sulfonic acid cartridges were washed twice with deionized water, and imazaquin was eluted into a 125-ml separatory funnel using 20 ml of potassium phosphate buffer (pH 6.5). After addition of 5 ml 1 *N* HCl and pH adjustment (pH 2.0), solutions were partitioned with 25 ml of methylene chloride twice. The lower phase containing imazaquin residues was collected and evaporated to dryness by rotary evaporation. Concentrated extracts were passed through a 20-μl syringe filter[3] and brought to 4 ml using potassium phosphate buffer (pH 6.5). Imazaquin was quantified via HPLC analysis as described above.

Data obtained from the runoff (total runoff volume and imazaquin loss) and field mobility studies were analyzed as a randomized complete block design with four replicates.

All data were subjected to ANOVA to test for significant interactions among years and days after treatment. Appropriate means were separated using Fisher's protected LSD test at the 5% significance level.

Bioavailable Imazaquin

The plant-available concentration of imazaquin was determined by a root length bioassay using corn as the indicator species. To establish a standard bioassay curve with 6 replications, 500 g of untreated soil was treated with formulated imazaquin to obtain final concentrations of 0, 5, 10, 30, 50, 80, and 100 ppb (v/v). Each concentration was applied with an aerosol sprayer[10] using 10 ml of deionized water as liquid carrier followed by thorough mixing of soil and herbicide. A separate standard curve was developed for each soil depth. Clear acetate tubing (3 cm diam) was cut into 20-cm lengths, and cheesecloth, secured with a rubber band, was placed over the bottom. Because of restriction of water movement encountered with subirrigation in preliminary studies, a cheesecloth wick was used to assure complete water saturation throughout the sample. Four 60-g replicates of each soil sample were placed into separate acetate tubes and subirrigated prior to planting. One 24-h pregerminated HyPerformer HS 9773 corn seed with a radicle length of approximately 3 ± 1 mm was planted in each tube and covered to exclude light from the roots. Tubes were placed in beakers and subirrigated as needed with deionized water. Bioassays were conducted in a growth chamber maintained at 30/25 ± 3 C (day/night). Day length was extended to 16 h with metal halide lamps at a minimum intensity of 300 μmol m^{-2} s^{-1} photosynthetic photon flux.

After a 6-d incubation period, corn root lengths were measured and compared to the standard response curve to predict the bioavailable concentration of imazaquin present. A logarithmic transformation of root lengths provided linear standard curves when regressed against the logarithmic transformed imazaquin concentration. Data were then subjected to ANOVA to test for significant year and treatment by sampling time interactions. Regression analysis was used to determine dissipation rate constants and half-lives were calculated according to the equation $DT_{50} = 0.693/K$, where K is the dissipation rate constant. The resulting half-lives were separated using Fisher's protected LSD.

Carryover

Plots used to evaluate field mobility in 1996 and 1997 were used to determine carryover potential of imazaquin the following year. Respective plots were subsoiled or received conventional tillage in the fall as described previously. Three rows of Pioneer 3167 corn was planted on April 1, 1997 and 1998. Corn was planted approximately 2.5 cm deep at a rate of 7.2 seeds m^{-1} of row. Tefluthrin [(2,3,5,6-tetrafluoro-4-methylphenyl)methyl-(1α,3α)-*Z*-(+-)-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate] was applied as an in-furrow insecticide treatment at 110 g ai ha^{-1}. In addition, three rows of DPL 50 cotton were planted on May 7, 1997, and May 5, 1998. Cotton was planted 2.5 cm deep at a rate of 13.5 kg ha^{-1} with aldicarb [2-methyl-2-(methylthio)propionaldehyde *O*-(methylcarbamoyl)oxime] as an in-furrow insecticide treatment. In both corn and cotton plots, 32% nitrogen solution was applied at a rate of 157 kg N ha^{-1}. Plots were maintained weed-free throughout the growing season by cultivation supplemented by hand weeding.

Visual injury was determined 2 and 5 wk after planting (WAP) using a scale of 0 (no injury) to 100 (plant death). Corn biomass data were obtained 13 and 15 WAP in 1997 and 1998, respectively. The height and weight of 20 representative corn plants, as well as the number of ears and their weight, were recorded. In addition, 20 representative cotton plants were mapped at 8 and 10 WAP in 1997 and 1998, respectively, using COTMAP (Bourland and Watson 1990). Data included plant height, position of the first fruiting node (FFN), number of fruiting sites, and the percentage of aborted fruiting sites at the first, second, and third fruiting positions. Corn and cotton yield were not evaluated because of late-season insect damage.

Field persistence experiments were conducted in a split plot arrangement with tillage treatments (main plot) and herbicide treatment (subplot) in a randomized complete block design with four replicates each year. Data were subjected to analysis of variance (ANOVA) to test for significant year interactions. Means were separated using Fisher's protected LSD test at the 5% significance level.

Results and Discussion

Runoff

Rainfall distribution and intensity following imazaquin application in 1997 and 1998 are presented in Table 1. Because of the presence of year by treatment interactions, runoff data were analyzed separately. Interactions were attributed to variations in rainfall distribution and duration, as well as environmental conditions between each year. Total natural rainfall during the sampling periods in 1997 and 1998 was 107 and 183 mm, respectively. Runoff in 1997 occurred 5, 6, 8, 24, and 34 d after imazaquin treatment (DAT) and in 1998 1, 2, 28, 39, and 40 DAT (Table 1). Although more rainfall occurred in 1998, the total volume of runoff water collected from both tillage systems was higher in 1997. The intensity of each rainfall and the time elapsed between rains may have caused differences in total runoff water. Although the amount of runoff collected varied within each rainfall, total volume collected was not different between tillage systems (Table 1).

The concentration of imazaquin detected after each rainfall was coupled with the runoff volume from each tillage system to determine total herbicide loss (Table 1). In 1997, the first runoff (36 mm) yielded the lowest detectable imazaquin concentration. Low soil moisture levels were present from the time of application until the first rainfall 5 DAT. Dry soil conditions may have concentrated imazaquin closer to sorptive surfaces, thus facilitating sorption to soil particles or precipitation. Temporary drying generally reduces the water film thickness coating soil particles, thereby increasing imazaquin adsorption, which may explain the low concentration of imazaquin detected in runoff water (Baughman and Shaw 1996; Goetz et al. 1986).

The second runoff in 1997 yielded the highest runoff volume and imazaquin concentration (Table 1). Because this rainfall (18 mm) occurred only 1 d after the first runoff, the soil was still completely saturated, thus facilitating runoff. In addition, water has been shown to compete with ima-

Table 1. Total runoff and herbicide loss from conventional tillage and subsoiling during the sampling period in 1997 and 1998.[a]

			Total runoff			Imazaquin loss					
Year	Rainfall event	Rainfall amount	Conventional tillage	Subsoiling	LSD (0.05)	Conventional tillage	Subsoiling	LSD (0.05)	Conventional tillage	Subsoiling	LSD (0.05)
	DAT	mm	kl ha^{-1}			mg ha^{-1}			% of applied		
1997	5	36	2.5	1.5	NS	40	40	NS	0.03	0.03	NS
	6	18	231.0	240.0	NS	1,800	1,500	NS	1.30	1.10	NS
	8	10	23.8	19.0	NS	280	200	NS	0.20	0.09	NS
	24	33	6.5	38.0	NS	bld	bld	—	—	—	—
	34	10	0.4	0.8	NS	bld	bld	—	—	—	—
Total		107	264.2	299.3	NS	2,120	1,740	NS	1.53	1.22	NS
1998	1	8	0.3	0.3	NS	420	420	NS	0.30	0.30	NS
	2	33	2.1	46.0	NS	3,200	2,600	NS	2.30	1.90	NS
	28	18	0.2	0.3	NS	30	30	NS	0.02	0.02	NS
	39	35	1.2	2.4	NS	20	20	NS	0.01	0.01	NS
	40	89	180.0	120.0	NS	1,400	1,600	NS	1.00	1.16	NS
Total		183	183.8	169.0	NS	5,070	4,670	NS	3.63	3.39	NS

[a] Abbreviations: bld, concentration below method detection limit (5 $\mu g\ kg^{-1}$); DAT, days after imazaquin treatment.

zaquin for binding sites (Barnes and Lavy 1991; Goetz et al. 1986; Renner at al. 1988). Therefore, it can be expected that high moisture levels may have promoted desorption of imazaquin, thereby making it more susceptible to loss in runoff. Imazaquin concentration declined with each subsequent rainfall to undetectable levels, regardless of tillage system. Imazaquin concentration was below the method's detection limit (5 $\mu g\ L^{-1}$) in runoff collected after rainfall occurring 24 and 34 DAT. In soils of the southern United States, imazaquin half-life has been reported to range between 6 and 21 d (Vencill et al. 1995), which may explain the absence of residues in the runoff at later sampling times. In 1997, 1.2 to 1.5% of the initial applied imazaquin was lost in runoff over time, regardless of tillage system.

In 1998, the first runoff occurred 1 DAT, resulting in loss of 0.3% of the applied imazaquin from both tillage treatments (Table 1). Imazaquin lost during this first rain was considerably higher than in 1997. This confirms earlier findings that herbicide concentrations are higher in runoff events that occur shortly after application (Wauchope 1978). Similar to 1997, the highest imazaquin concentration was detected after the second runoff, which occurred 2 DAT in 1998. The second runoff was only 1 d after a previous rainfall, and the soil surface was still saturated, facilitating runoff. Concentration in runoff diminished over time, with approximately 3.5% of the applied imazaquin being lost, regardless of tillage system.

The data suggest that imazaquin concentration in runoff water diminished over time as a result of increased plant uptake, adsorption, and microbial and chemical degradation. Although the concentration of imazaquin in runoff varied, no differences due to tillage systems was observed (Table 1).

Field Mobility and Persistence

Because significant year by tillage interactions were observed, data are presented for each year. No differences in total extractable imazaquin concentration were detected as a result of implementation of different tillage systems. The highest concentration was detected in samples taken immediately after imazaquin application in each year (Figure 1). Based on an 8-cm soil depth, imazaquin application at 140 g ai ha^{-1} would result in an initial soil concentration of 125 $\mu g\ kg^{-1}$. In this study, initial concentrations ranged from 110 to 190 $\mu g\ kg^{-1}$.

Temperature and natural precipitation for 10 wk following imazaquin application in 1996, 1997, and 1998 are shown in Table 2. In 1996, imazaquin dissipation was initially impeded, which can be attributed to environmental conditions. Low soil moisture conditions before and shortly after application may have increased imazaquin adsorption, thereby reducing concentrations in the soil solution and microbial degradation (Cantwell et al. 1989; Flint and Witt 1997; Goetz et al. 1986; Loux and Reese 1992). Renner et al. (1988) reported that the soil moisture content at the time of herbicide application can have a critical effect on herbicide availability. Flint and Witt (1997) reported that lower soil moisture and temperatures cause longer persistence of herbicides that are degraded by microorganisms. In general, a 10 C decrease in temperature is associated with a two- to threefold increase in half-life (Flint and Witt 1997; Walker 1987). A 10 C decrease in temperature observed 2 WAT coupled with varying soil moisture conditions in 1996 (Table 2) may have contributed to increased persistence observed at early sampling dates (Figure 1).

The shortest half-lives of imazaquin, based on total extractable imazaquin concentration, occurred in 1996 and were 8 and 11 d in the conventional and subsoiling treatments, respectively. In 1997, the imazaquin half-lives were 11 and 16 d, and in 1998, half-lives were 19 and 25 d. There was no significant difference between the calculated half-lives under the different tillage systems in any year. These results confirm earlier findings that tillage systems (conventional and reduced tillage) did not affect dissipation of preemergence soil-applied herbicides including imazaquin (Curran et al. 1992).

Bioavailable Imazaquin

ANOVA indicated imazaquin concentrations within each soil depth could be averaged over years. Tillage systems did not affect the plant-available concentration of imazaquin (Figure 2). The highest imazaquin concentration, approxi-

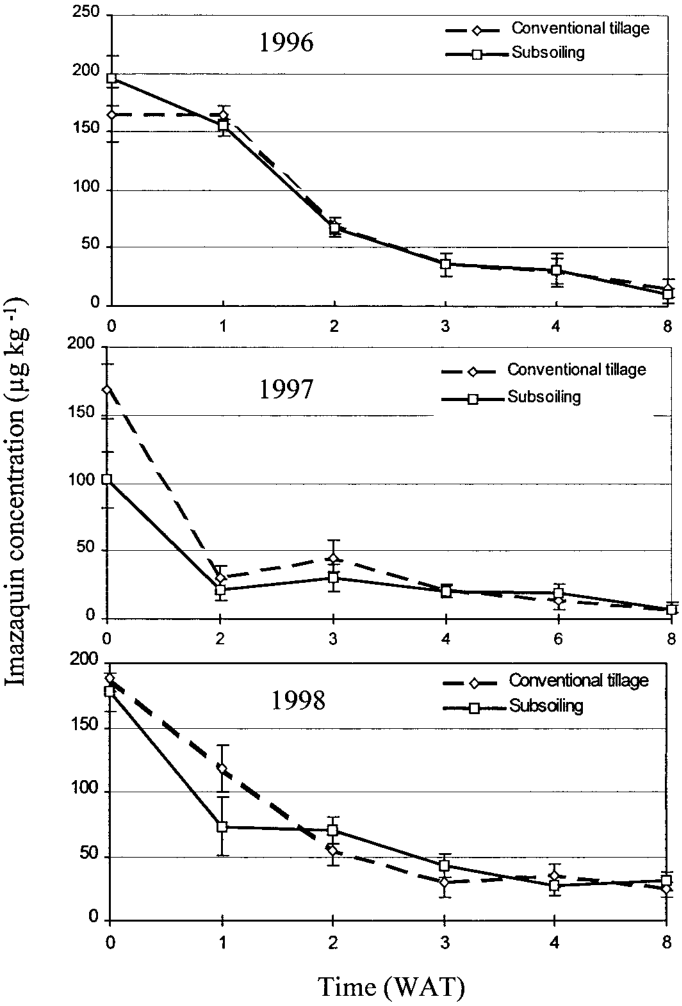

FIGURE 1. Effect of tillage systems on total imazaquin concentration in a Sharkey clay soil (0–8 cm) over time as determined by chemical extraction. Error bars represent ± 1 standard error of the mean.

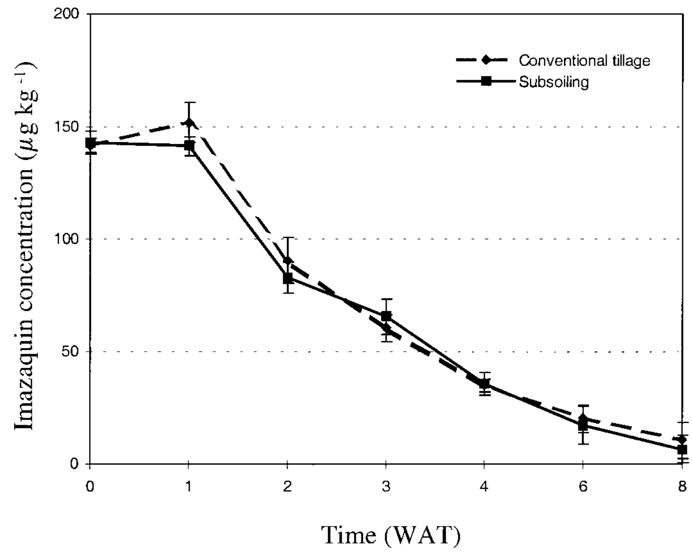

FIGURE 2. Effect of tillage systems on plant-available imazaquin concentration in a Sharkey clay soil over time as determined by bioassay procedure (averaged over years). Error bars represent ± 1 standard error of the mean.

mately 145 μg kg^{-1}, was detected in samples taken immediately after application, regardless of tillage treatment. Imazaquin soil half-lives were 12 and 16 d in the two tillage systems and were not significantly different. Hence in the current study, similar results were obtained using two distinct analytical methods: chemical extraction and bioassay.

Carryover

Because of the absence of year by tillage interactions, corn biomass and cotton mapping data could be averaged over years; however, injury symptoms were analyzed on a yearly basis. Temperature and natural precipitation for 10 wk following planting of corn in 1997 and 1998 are shown in Table 3. In 1997, cotton injury was visible as slight stunting, while imazaquin injury to corn was characterized by purple discoloration and interveinal chlorosis. Two WAP, cotton

TABLE 2. Average temperature ([max + min]/2) and total precipitation for 10 wk following planting of soybean (*Glycine max*) and imazaquin application in 1996, 1997, and 1998.

	1996[a]		1997[b]		1998[c]	
Time	Temperature	Precipitation	Temperature	Precipitation	Temperature	Precipitation
wk	C	mm	C	mm	C	mm
0	32.8	0	23.4	54.3	26.9	41.7
1	28.2	27.9	25.7	11.7	29.0	0
2	23.3	56.6	27.9	0	29.0	7.6
3	23.7	7.3	28.1	35.2	29.0	0
4	27.3	62.2	27.3	15.7	29.7	19.5
5	28.1	1.5	28.0	7.6	28.4	125.5
6	29.2	5.3	28.8	26.9	25.9	0
7	28.1	0	30.6	11.2	32.2	0
8	26.8	11.9	25.7	0	29.4	0
9	28.8	3.8	29.4	51.2	28.3	19.8
10	26.1	74.7	29.0	5.8	29.7	12.3
Total		251.2		219.6		226.4
Average	30.24		30.39		31.75	

[a] Imazaquin application on May 15, 1996 (soil samples taken at 0, 1, 2, 3, 4, 8 wk after treatment of WAT).
[b] Imazaquin application on June 4, 1997 (soil samples taken at 0, 2, 3, 4, 6, 8 WAT).
[c] Imazaquin application on June 3, 1998 (soil samples taken at 0, 1, 2, 3, 4, 8 WAT).

Table 3. Average temperature ([max + min]/2) and total precipitation for 10 wk following planting of corn (*Zea mays*) in 1997 and 1998.

Time	1997[a] Temperature	1997[a] Precipitation	1998[b] Temperature	1998[b] Precipitation
wk	C	mm	C	mm
0	17.0	27.9	19.2	0
1	11.4	0	14.3	34.5
2	16.2	0	19.4	54.1
3	15.5	82.5	21.9[c]	1[c]
4	16.6	60.4	24.4	0
5	20.0[d]	0[d]	26.7	0
6	21.5	0	27.2	111.5
7	22.1	13.9	27.9	12.9
8	22.7	77.7	24.8	24.8
9	22.7	0	29.0	7.1
10	25.7	60.4	29.0	1
Sum		322.8		246.9
Average	21.14		26.38	

[a] Temperature and precipitation after corn planting on April 11, 1997.
[b] Temperature and precipitation after corn planting on April 1, 1998.
[c] Temperature and precipitation after cotton planting on May 5, 1998.
[d] Temperature and precipitation after cotton (*Gossypium hirsutum*) planting on May 7, 1997.

Table 4. Cotton (*Gossypium hirsutum*) and corn (*Zea mays*) height measurements (1998) and visual injury (1997) at 2 wk after planting was affected by tillage system and imazaquin applied preemergence at 140 g ai ha^{-1}.

Tillage system	Imazaquin application	Height Cotton	Height Corn[a]	Injury Cotton	Injury Corn
		cm	cm	%	%
Conventional	Yes	60.3	174.6	5.2	3.7
Conventional	No	61.9	179.7	0	0
Subsoiling	Yes	69.6	189.4	14.6	10.3
Subsoiling	No	67.6	187.5	0	0
LSD (0.05)		6.9	4.1	NS	NS

[a] Value represents average of 20 plants.

injury ranged from 5 to 15%, whereas imazaquin residues caused 3 to 10% injury to corn with no differences between tillage systems (Table 4). Injury symptoms were transient, and 5 WAP, no cotton or corn injury was observed (data not shown). Apparently plants were able to recover rapidly under the warm, humid conditions present later in the growing season. In 1998, no crop injury was observed, indicating that imazaquin had dissipated to concentrations that were below the threshold for cotton and corn injury (data not shown).

The elevated injury observed 2 WAP in 1997 is likely explained by soil and environmental conditions after planting (Table 3). Because soil water can compete with herbicide molecules for binding sites to soil colloids (Baughman and Shaw 1996; Johnson et al. 1995; Mangels 1991; Regitano et al. 1997), higher rainfall following cotton and corn planting in 1997 may have increased imazaquin concentration in the soil solution and promoted plant uptake (Table 3). Furthermore, cool temperatures in the spring of 1997 may have increased the susceptibility of plants to imazaquin by reducing the rate of metabolism (Malefyt and Quakenbush 1991). These data confirm findings of increased injury from imazaquin residues under cool and wet conditions (Johnson et al. 1995).

Vegetative and reproductive cotton growth parameters, including total fruiting positions and the percentage of aborted fruiting sites at the first, second, and third position, were not affected by tillage systems or imazaquin application (data not shown). Additionally, the position of the first fruiting node (FFN), a measure of earliness and yield potential, was not affected by tillage system or imazaquin application the previous year (data not shown). Because no elevation of the FFN was noted, which would have been an indication of yield loss, these data suggest that cotton was able to recover completely from early-season injury caused by imazaquin. Furthermore, corn biomass data were not affected by tillage systems in 1997 and 1998 (data not shown). Collectively, these data suggest that under the environmental conditions encountered during the course of this study, cotton and corn may be planted in a Sharkey clay soil the year following use of imazaquin at the labeled rate of 140 g ai ha^{-1}, because imazaquin dissipated to a level below the threshold for cotton and corn injury, regardless of tillage system. However, the current imazaquin label contains an 18-mo rotation restriction for cotton. In addition, corn can be planted the spring after a single imazaquin application unless extreme drought conditions develop within 6 mo following the application date (Anonymous 1999).

Subsoiling in combination with imazaquin produced significantly taller cotton and corn plants in 1998 (Table 4). Subsoiling of heavy clay soils has been shown to disrupt compacted soil structures, thereby increasing water infiltration rate (Smith 1995; Wesley et al. 1994). As a result, plants may have been able to extend their roots into deeper soil layers. It seems likely that both cotton and corn plants experienced less severe water deficit stress, which resulted in increased plant height in 1998. However, no differences were noted in plant height in 1997 (data not shown). Rainfall early in the season was much higher in 1997 than in 1998 (Table 1), which apparently negated any beneficial effect of subsoiling. Thus, the response to subsoiling is variable based on rainfall and soil moisture during the portions of the growing season.

Subsoiling of a Sharkey clay soil did not affect the total amount of runoff water after natural rainfall or the amount of imazaquin lost. In addition, total extractable and plant-available imazaquin concentrations were not influenced by tillage systems. Furthermore, imazaquin persistence was not prolonged because of implementation of different tillage systems. Therefore, adoption of subsoiling techniques on heavy clay soils in the Mississippi Delta can be expected to have minimal affect on the environmental fate of imazaquin.

Sources of Materials

[1] Glass fiber filter, Baxter Diagnostics Inc., 1430 Waukegan Road, McGaw Park, IL 60085-6787.

[2] Acrodisc LC 13 PVDF syringe filter, Baxter Diagnostics, Inc., 1430 Waukegan Road, McGaw Park, IL 60085-6787.

[3] HPLC 1100 series, Hewlett-Packard Company, 2850 Centerville Road, Wilmington, DE 19808-1610.

[4] Econosphere C18 5 μ column, Autech Assoc., Inc., 2951 Waukegan Road, Deerfield, IL 60015.

[5] Extraction method M-1854, American Cyanamid Company,

Agricultural Research Division, P.O. Box 400, Princeton, NJ 08540.

[6] Celite 545 AW, VWR Scientific Products, 1430 Waukegan Road, McGaw Park, IL 60085.

[7] Whatman glass microfiber filter 934-AH, VWR Scientific Products, 1430 Waukegan Road, McGaw Park, IL 60085.

[8] Varian SPE octadecyl cartridge (C-18), 1,000 mg, Varian Assoc., Inc., 24201 Frampton Avenue, Harbor City, CA 90710.

[9] Varian SPE benzene sulfonic acid cartridge (SCX), 500 mg, Varian Assoc., Inc., 24201 Frampton Avenue, Harbor City, CA 90710.

[10] Chromist aerosol spray, VWR Scientific Products, 1430 Waukegan Road, McGaw Park, IL 60085.

Literature Cited

Ahrens, W. H., ed. 1994. Herbicide Handbook. 7th ed. Champaign, IL: Weed Science Society of America. pp. 165–166.

Anonymous. 1999. Weed Control Guidelines for Mississippi. Mississippi State, MS: Mississippi State University Extension Service Publication 1532. 50 p.

Barnes, C. J. and T. L. Lavy. 1991. Injury and yield response of selected crops to imazaquin and norflurazon residues. Weed Technol. 5:598–606.

Basham, G. W., T. L. Lavy, L. R. Oliver, and H. D. Scott. 1987. Imazaquin persistence and mobility in three Arkansas soils. Weed Sci. 35:576–582.

Baughman, T. A. and D. R. Shaw. 1996. Effect of wetting/drying circles on dissipation patterns of bioavailable imazaquin. Weed Sci. 44:380–382.

Bourland, F. M. and C. E. Watson, Jr. 1990. COTMAP, a technique for evaluating structure and yield of cotton plants. Crop Sci. 30:224–226.

Cantwell, R. J., R. A. Liebl, and F. W. Slife. 1989. Biodegradation characteristics of imazaquin and imazethapyr. Weed Sci. 37:815–819.

Curran, W. S., R. A. Liebl, and F. W. Simmons. 1992. Effects of tillage and application method on clomazone, imazaquin, and imazethapyr persistence. Weed Sci. 40:482–489.

Flint, J. L. and W. W. Witt. 1997. Microbial degradation of imazaquin and imazethapyr. Weed Sci. 45:586–591.

Goetz, A. J., G. Wehtje, R. H. Walker, and B. Hajek. 1986. Soil solution and mobility characterization of imazaquin. Weed Sci. 34:788–793.

Griffith, D. R., J. F. Moncrief, D. J. Eckert, J. B. Swan, and D. D. Breitbach. 1992. Crop response to tillage systems. Pages 25–33 *in* Conservation Tillage Systems and Management. MidWest Plan Service-45. Ames, IA: Iowa State University.

Johnson, D. H., R. E. Talbert, and D. R. Horton. 1995. Carryover potential of imazaquin to cotton, grain sorghum, wheat, rice, and corn. Weed Sci. 43:454–460.

Johnson, D. H. and R. E. Talbert. 1996. Cotton (*Gossypium hirsutum*) response to imazaquin and imazethapyr soil residues. Weed Sci. 44:156–161.

Locke, M. A. and C. T. Bryson. 1997. Herbicide–soil interactions in reduced tillage and plant residue management systems. Weed Sci. 45:307–320.

Loux, M. M., R. A. Liebl, and F. W. Slife. 1989. Adsorption of imazaquin and imazethapyr on soils, sediment, and selected adsorbents. Weed Sci. 37:712–718.

Loux, M. M. and K. D. Reese. 1992. Effect of soil pH on adsorption and persistence of imazaquin. Weed Sci. 40:490–496.

Malefyt, T. and L. Quakenbush. 1991. Influence of environmental factors on the biological activity of the imidazolinone herbicides. Pages 103–127 *in* D. L. Shaner and S. L. O'Conner, eds. The Imidazolinone Herbicides. Boca Raton, FL: CRC Press.

Mangels, G. 1991. Behavior of the Imidazolinone herbicides in soil—a review of literature. Pages 191–209 *in* D. L. Shaner and S. L. O'Conner, eds. The Imidazolinone Herbicides. Boca Raton, FL: CRC Press.

Mills, J. A. and W. W. Witt. 1991. Dissipation of imazaquin and imazethapyr under conventional and no-tillage soybean (*Glycine max*). Weed Technol. 5:586–591.

Regitano, J. B., M. Bischoff, L. S. Lee, J. M. Reichert, and R. F. Turco. 1997. Retention of imazaquin in soil. Environ. Toxicol. Chem. 17:397–404.

Renner, K. A., W. F. Meggitt, and R. A. Leavitt. 1988. Influence of rate, method of application, and tillage on imazaquin persistence in soil. Weed Sci. 36:90–95.

Smith, L. A. 1995. Cotton response to deep tillage with controlled traffic on clay. Trans. Am. Soc. Agric. Eng. 38:45–50.

Vencill, W. K., P. A. Banks, M. Barrett, B. Brecke, N. Rhodes, P. Santelman, D. Shaw, R. Talbert, and J. B. Weber. 1995. Dissipation of imazaquin in Southern soils. J. Environ. Sci. Health B 30:621–635.

Walker, A. 1987. Herbicide persistence in soil. Rev. Weed Sci. 3:1–17.

Wauchope, R. D. 1978. The pesticide content of surface water draining from agricultural fields—a review. J. Environ. Qual. 7:459–472.

Wesley, R. A. and L. A. Smith. 1991. Response of soybean to deep tillage with controlled traffic on clay soil. Trans. Am. Soc. Agric. Eng. 34:113–119.

Wesley, R. A., L. A. Smith, and S. R. Spurlock. 1994. Fall Deep Tillage of Clay: Agronomic and Economic Benefits to Soybeans. Mississippi State, MS: Mississippi State University, Mississippi Agricultural and Forestry Experimental Station Bulletin 1015. 8 p.

Received April 28, 2000, and approved February 21, 2001.